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(54) Abstract Title
Optical demultiplexer with flattened spectral response using taper waveguides

(57) An optical wavelength demultiplexer, capable of exhibiting flat spectral response characteristics while minimizing insertion loss and used in WDM systems, includes a first slab waveguide 212 for dividing powers of input optical signals coupled from the input optical waveguides 210, an arrayed waveguide grating 214 for guiding the optical signals from the first slab waveguide therethrough in such a fashion that the optical signals have constant phase difference in neighbouring waveguides, a second slab waveguide 216 in which the optical signals from the arrayed waveguide grating converge into the focal positions according to their wavelengths, and taper waveguides (enlarged) interposed between the second slab waveguide 216 and output waveguides 218.
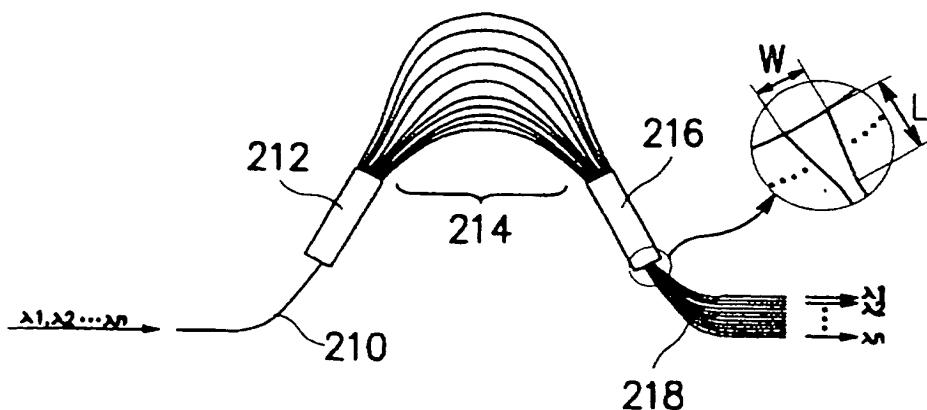

FIG. 2

GB 2 349 957 A

FIG. 1

FIG. 2

SECOND SLAB
WAVEGUIDE

L

W

318

317a

317

317b

317c

OUTPUT
WAVEGUIDE

FIG. 3

LOCAL MODE FIELD
(FUNDAMENTAL MODE)

FOCAL FIELD

POSITION ON IMAGE PLANE(μm)
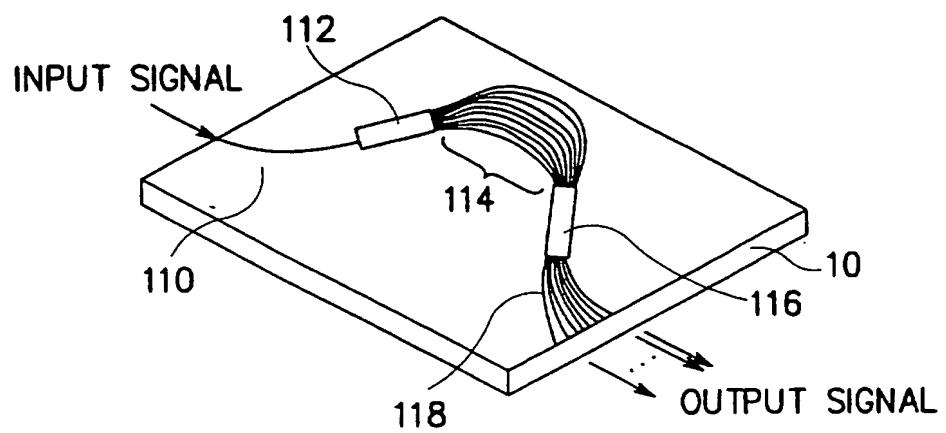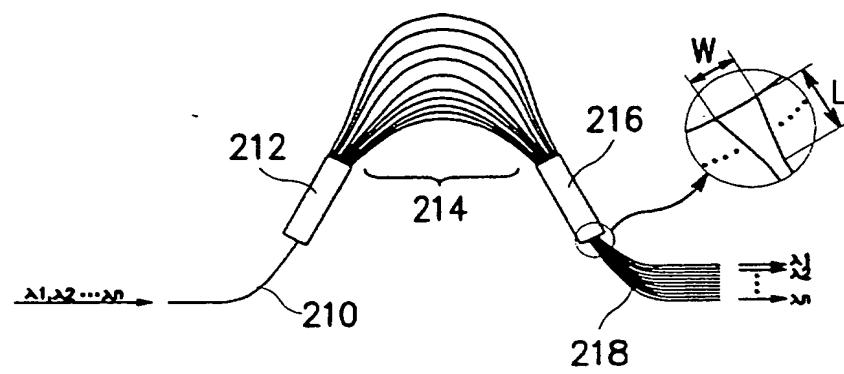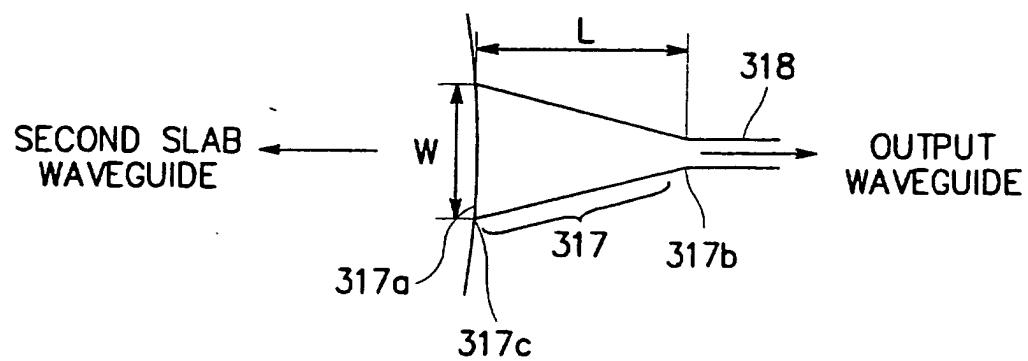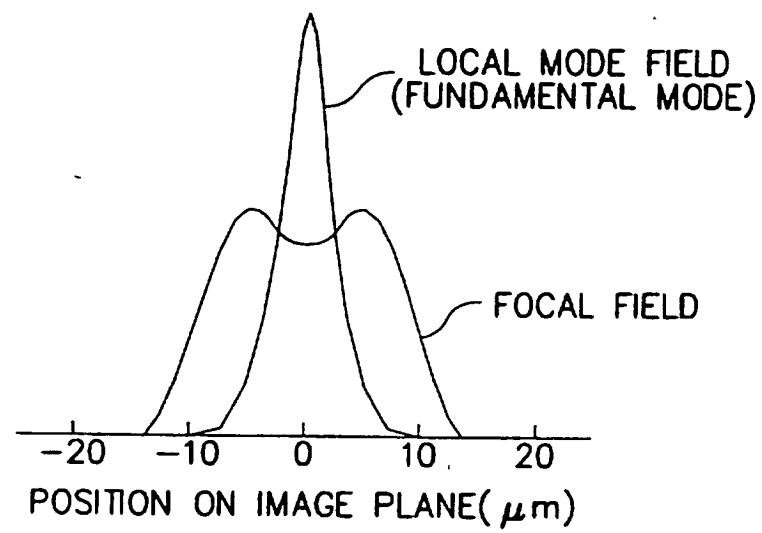
FIG. 4A
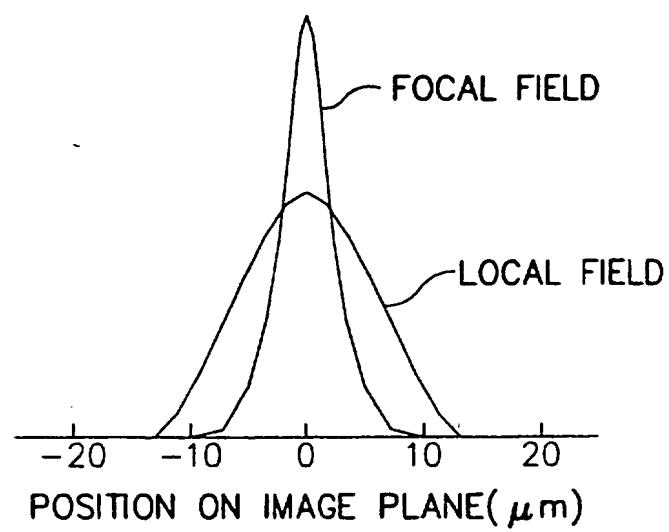
FIG. 4B
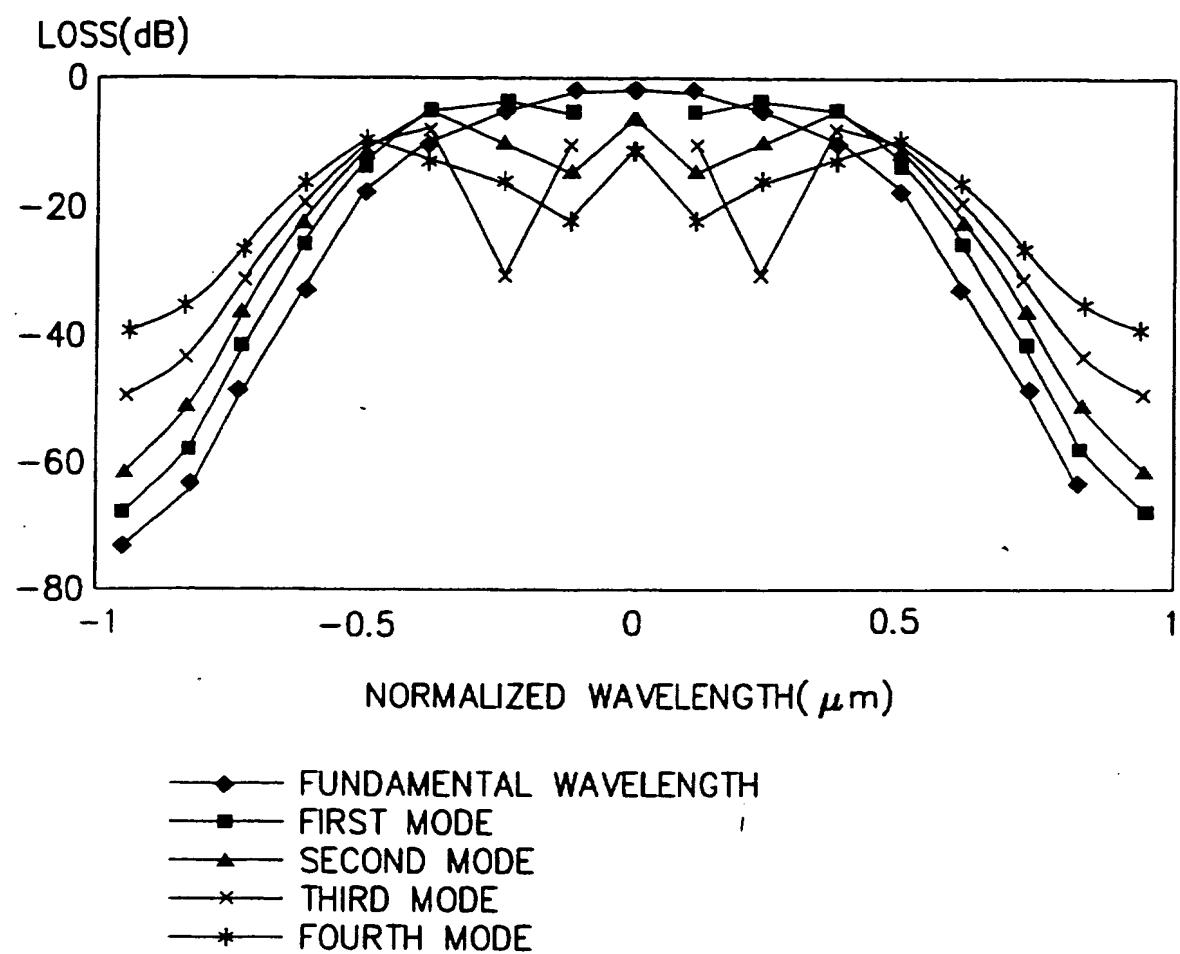
FIG. 5
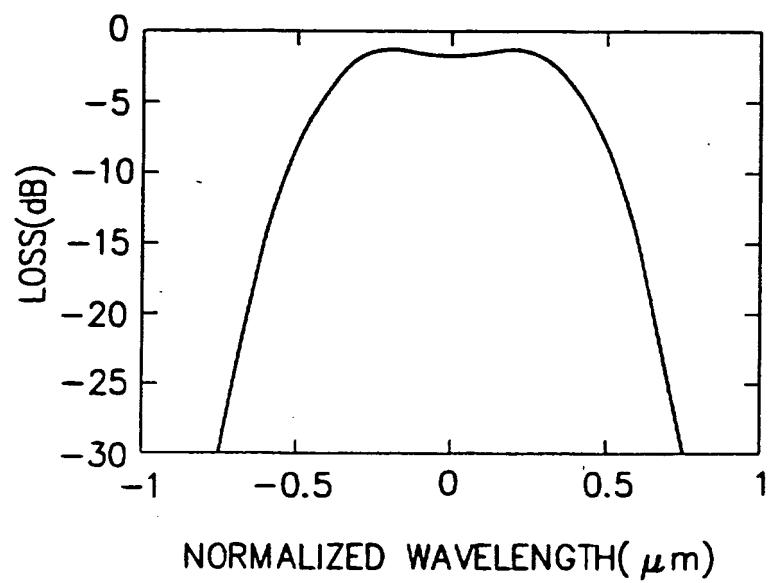
FIG. 6

DEMULTIPLEXER WITH FLATTENED

SPECTRAL RESPONSE

BACKGROUND OF THE INVENTION

5

The present invention relates to an optical wavelength demultiplexer for use in a wavelength-division multiplexing (WDM) system, and more particularly to an optical wavelength demultiplexer capable of exhibiting

10 flat spectral response characteristics while minimizing insertion loss.

The operation of an optical wavelength demultiplexer using an arrayed waveguide grating (AWG) structure can be

15 defined using a grating equation describing dispersion characteristics of incident light resulting from a diffraction of the incident light under the condition in which an array of waveguides is regarded as a diffraction grating. Such an optical wavelehgth demultiplexer is

20 referred to as an AWG optical wavelength demultiplexer.

Such an AWG optical wavelength demultiplexer is an optical device used in a WDM system to couple optical signals of different wavelengths or to divide an optical

25 signal into those of different wavelengths. Light incident to such an AWG optical wavelength demultiplexer varies in phase while passing through three parts of the AWG optical wavelength demultiplexer, that is, a first slab waveguide, an AWG, and a second slab waveguide. The

30 phase variations of light respectively generated by the parts of the AWG optical wavelength demultiplexer are

summed at the final output plane of the AWG optical wavelength demultiplexer, so that a reinforced interference effect is obtained at the final output plane. The above mentioned grating equation is an

5 equation for deriving a condition in which a reinforced interference effect is obtained at the final output plane of the AWG optical wavelength demultiplexer by virtue of the sum of the phase variations. Here, the final output plane is an interface of the second slab waveguide with

10 an output waveguide. Assuming that light is incident to a central input waveguide, the above mentioned grating equation is expressed as follows:

[Expression 1]

15

$$n_s d \sin \theta + n_c \Delta L = m\lambda$$

where "n_s" represents effective refractive index of the first and second slab waveguides, "n_c" an effective

20 refractive index of the AWG, "d" the pitch of the AWG, "m" the order of diffraction, "ΔL" a length difference between adjacent waveguides in the AWG, and "λ" the wavelength of incident light.

25 The central operating wavelength λ_0 corresponds to the wavelength of light when "θ" in Expression 1 corresponds to zero. This central operating wavelength λ_0 is defined as follows:

[Expression 2]

$$\lambda_0 = \frac{n_C \Delta L}{m}$$

5

From Expression 1, it is possible to derive an equation of a variation in the diffraction angle of light depending on a variation in wavelength. After differentiating both sides of Expression 1 with regard to

10   the wavelength λ (using the approximation $\theta \approx \sin \theta$ for small values of θ), the following Expression 3 is derived:

[Expression 3]

15

$$\frac{d\theta}{d\lambda} = \frac{m}{n_s d}$$

Referring to Expression 3, it can be found that a variation in the wavelength of incident light results in

20   a variation in the wavefront direction of the light. Such a variation in the wavefront direction of the light results in a variation in the main lobe position of an interference pattern formed on the image plane of the second slab waveguide.

25

The spectral response of the optical wavelength demultiplexer can be derived using an overlap integration between the interference pattern formed on the image plane of the second slab waveguide and the mode of the

30   output waveguide connected to the second slab waveguide.

However, typical optical wavelength demultiplexers exhibit Gaussian spectral responses because their interference patterns and output waveguide modes have a Gaussian form. When optical wavelength demultiplexers exhibiting such a Gaussian spectral response are applied to a system, it is necessary to accurately control a spectral variation occurring in a laser diode which may serve as a source for the system. Where such optical wavelength demultiplexers are coupled together in series, a reduction in the passband width of the spectral response occurs between adjacent ones of the optical wavelength demultiplexers. This results in a disadvantage in that the installation and maintenance cost of the system increase.

In order to solve the above mentioned problem, the spectral response in each channel should be flat. Two methods have been proposed to obtain flat spectral response. The following description will be made in conjunction with these methods.

One method is to adjust the optical path length of the AWG. This method is disclosed in U.S. Patent No. 5,467,418 issued to Corrado Dragone, Lucent Technologies and is entitled "FREQUENCY ROUTING DEVICE HAVING A SPATIALLY FILTERED OPTICAL GRATING FOR PROVIDING AN INCREASED PASSBAND WIDTH". In accordance with this method, the field distribution of light incident to the second slab waveguide has the form of a sine function. A diffraction phenomenon occurring in the second slab

waveguide can be regarded as a Fourier transform of
incident light occurring at the output plane. In order
to obtain a flat output profile, the above method
suggests adjusting the profile of incident light to have
5 the form of a sine function corresponding to an inverse
Fourier transform of a desired output. In order to
obtain such an incident light profile, it is necessary to
adjust the lengths of waveguides in the AWG in such a
fashion that there is a length difference corresponding
10 to a half-wavelength in at least a portion of the AWG
region while intentionally giving loss in accordance with
the envelope thereof. For this reason, there is a
disadvantage in that the entire device involves
additional insertion loss corresponding to the
15 intentional loss given to the AWG.

Another method is to apply a parabolic horn waveguide to
an input waveguide coupled to the first slab waveguide of
a wavelength demultiplexer in order to obtain flat
20 spectral response characteristics. This method is
disclosed in a patent application filed by K. Okamoto,
NTT, Japan. The method proposed by K. Okamoto, et al. is
disclosed in detail in an article "FLAT SPECTRAL RESPONSE
ARRAYED WAVEGUIDE GRATING MULTIPLEXER WITH PARABOLIC
25 WAVEGUIDE HORNS", Electronics Letters, 32, pp. 1961-1962,
1996.

In accordance with this method, the parabolic horn
waveguide utilizes the characteristics of the wavelength
30 demultiplexer allowing the mode profile at the first slab
input plane to be reconstructed at the output image plane

of the second slab waveguide, as it is, thereby forming the input waveguide mode profile into a double peak profile while obtaining a flat final spectral response at the output plane using an overlap integration for the

5 double peak profile. Although it is unnecessary to give an intentional loss, as in the aforementioned method, this method inevitably involves loss resulting from the fact that the double peak image at the output image plane does not correspond to the local mode of the output

10 waveguide.

As apparent from the above description, both the above mentioned conventional methods inevitably involve additional loss of 2 to 3 dB, as compared to the case

15 involving a Gaussian spectral response, because they are adapted to only vary the image at the image plane while still maintaining the mode of the output waveguide.

SUMMARY OF THE INVENTION

20

Therefore, the present invention has been made in view of the above mentioned problems, and an aim of the invention is to provide an AWG optical wavelength demultiplexer capable of achieving a reduction in loss.

25

Another aim of the invention is to provide an AWG optical wavelength demultiplexer capable of exhibiting a flattened spectral response.

30 Another aim of the invention is to provide an AWG optical wavelength demultiplexer capable of exhibiting a

flattened spectral response while eliminating additional loss which may be involved in conventional methods.

According to an aspect of the invention, at least some of these aims are addressed by using a taper waveguide arranged between the second slab waveguide and the output waveguide.

Accordingly, the present invention provides an optical wavelength demultiplexer, comprising:

first means, for power-dividing the input optical signals coupled from one or more input optical waveguides;

second means, comprising a number of waveguides, each adapted to receive a respective power-divided optical signal, and for introducing a constant phase difference between the power-divided optical signals in neighbouring waveguides;

third means, for recombining and wavelength-dividing the optical signals output from the second means, and supplying the resultant optical signals to one or more respective output waveguides; and

taper waveguides interposed between the third means and the output waveguides and adapted to obtain a flat spectral response.

The first means may comprise a first slab waveguide. The second means may comprise an arrayed waveguide grating.

The third means may comprise a second slab waveguide.

The taper waveguides are preferably further adapted to minimise an insertion loss. The taper waveguides may be a linear taper waveguide. The taper waveguides may have an adiabatic structure, and be adapted to reduce a power exchange among waveguide modes during passage of optical signals therethrough. The taper waveguides may have a multi-mode structure at the output terminal of the third means. The taper waveguides may have a same size as the size of the output waveguides, at an output terminal thereof, thereby to facilitate the coupling of the output waveguides so as to guide the optical signals into the output waveguides.

BRIEF DESCRIPTION OF THE DRAWINGS

The above, and further, objects, characteristics and advantages of the present invention will become more apparent by reference to the following description of certain embodiments thereof, in conjunction with the attached drawings in which:

Fig. 1 is an enlarged schematic perspective view illustrating a low loss optical wavelength demultiplexer chip with a flat spectral response using an AWG in accordance with an embodiment of the present invention;

Fig. 2 is an enlarged schematic perspective view illustrating a pattern of the AWG optical wavelength demultiplexer shown in Fig. 1;

Fig. 3 is an enlarged schematic view illustrating an output taper waveguide according to an embodiment of the present invention;

5

Fig. 4A is a graph depicting a fundamental (local mode) field of an output waveguide and a focal field formed on an image plane in a conventional AWG optical wavelength demultiplexer.

10

Fig. 4B is a graph depicting a fundamental (local mode) field of an output waveguide and a focal field formed on an image plane in the AWG optical wavelength demultiplexer of the present invention.

15

Fig. 5 is a graph depicting an overlap integration between an interference pattern formed on an image plane and each of the modes of an output waveguide in the AWG optical wavelength demultiplexer of the present

20 invention; and

Fig. 6 is a graph depicting loss characteristics calculated for one channel of the AWG optical wavelength demultiplexer of the present invention.

25

DETAILED DESCRIPTION EMBODIMENTS OF THE INVENTION

Fig. 1 is an enlarged schematic perspective view illustrating a low loss optical wavelength demultiplexer

30 chip with a flat spectral response using an arrayed waveguide grating (AWG) in accordance with an embodiment

of the present invention.   Fig. 2 is an enlarged
schematic perspective view illustrating a pattern of the
AWG optical wavelength demultiplexer shown in Fig. 1.

5   As shown in Fig. 1, the optical wavelength demultiplexer
has a waveguide pattern which is formed on a substrate 10
by subjecting the substrate 10 to several patterning
processes.   Here, the "waveguide pattern" includes
waveguides through which an optical signal passes.   The
10   AWG optical wavelength demultiplexer includes at least
one input waveguide 110 for receiving optical signals of
different wavelengths, a first slab waveguide 112 for
dividing optical power received from the input waveguide
110, and an AWG 114 coupled to the output terminal of the
15   first slab waveguide 112 and adapted to guide optical
signals received from the first slab waveguide 112 in
such a fashion that those optical signals have constant
phase difference in neighbouring waveguides.   The AWG
optical wavelength demultiplexer also includes a second
20   slab waveguide 116 coupled to the output terminal of the
AWG 114 and adapted to separate or couple the wavelengths
of the optical signals outputted from the AWG 114, and
taper waveguides (shown in Figs. 2 and 3) arranged
between the output terminal of the second slab waveguide
25   116 and output waveguides 118 and adapted to obtain a
flat spectral response.

Now, the operation of the AWG optical wavelength
demultiplexer having the above mentioned configuration
30   will be described.   Optical signals received in at least
one input waveguide 110 pass though the first slab

waveguide 112 and then enter the AWG 114 having a plurality of waveguides with different lengths. The optical signals emerging from the AWG 114 have different phases, respectively. The optical signals of different

5   phases are then incident to the second slab waveguide 116 in which a reinforcement and interference occurs for the optical signals. As a result, the optical signals are focused at one of the output waveguides 118 in a self-imaging fashion. The resultant image is then outputted

10   from the associated output waveguide 118.

The operation principle of the AWG optical wavelength demultiplexer according to the illustrated embodiment of the present invention will now be described in

15   conjunction with Fig. 2.

AWG optical wavelength demultiplexers are implemented by an arrayed waveguide grating configured to vary its wavefront direction depending on a variation in the

20   wavelength of light. In such AWG optical wavelength demultiplexers, a linear dispersion indicative of a variation in the shift of the main peak of an interference pattern on a focal plane (or image plane) depending on a variation in wavelength can be expressed

25   as follows:

[Expression 4]

$$\frac{dx}{d\lambda} = \frac{fm}{n_s d}$$

5   where, "f" represents the focal length of a slab
waveguide, "m" the order of diffraction, "d" the pitch of
an AWG, and "n_s" the effective refractive index of the
slab waveguides, respectively.

10   In accordance with Expression 4, the wavelength
distribution of an optical signal incident to the AWG
optical wavelength demultiplexer is spatially focused on
the image plane of the second slab waveguide 216.
Accordingly, where a plurality of output waveguides 218
15   are coupled to the image plane while being spaced apart
from one another by a predetermined distance, it is
possible to implement an AWG optical wavelength
demultiplexer having a wavelength spacing determined by
the location of the output waveguides 218.

20

Optical signals respectively outputted from the arrayed
waveguides of the AWG 214 while having different phases
are subjected to a Fraunhofer diffraction while passing
through the second slab waveguide 216. Accordingly, an
25   interference pattern is formed on the image plane. The
Fraunhofer diffraction describes the relation between the
input optical signals and the diffraction pattern in the
form of a Fourier transform. Accordingly, if one of the
input optical signals or diffraction pattern is known, it
30   is then possible to calculate the amplitude and phase of

the remaining one using a Fourier transform or an inverse Fourier transform.

In accordance with the present invention, as shown in
5 Fig. 3, a taper waveguide 317 is interposed between the second slab waveguide and the output waveguide 318. The taper waveguide 317 is adapted to allow the AWG optical wavelength demultiplexer to obtain a flat spectral response while involving low loss.
10

Now, the taper waveguide 317 will be described in detail.

The taper waveguide 317 is interposed between the output terminal of the second slab waveguide and the output
15 waveguide 318. The taper waveguide 317 is a multi-mode taper waveguide having a plurality of waveguide modes. This taper waveguide 317 serves as an input terminal of the output waveguide 318.

20 Preferably, the taper waveguide 317 has an adiabatic structure in order to prevent a power exchange among waveguide modes during passage of optical signals therethrough. The taper waveguide 317 enlarges the acceptance angle of incident light, thereby minimizing
25 optical loss.

The input end 317a of the taper waveguide 317 facing the second slab waveguide has a multi-mode structure. On the other hand, the output end 317b of the taper waveguide
30 317 coupled to the output waveguide 318 has the same size as the output waveguide 318.

Fig. 4A is a graph depicting a fundamental (local mode) field of an output waveguide and a focal field formed on an image plane in a conventional AWG optical wavelength

5   demultiplexer.   Referring to Fig. 4A, it can be found that an interference pattern having a double peak profile is formed on the image plane in accordance with the conventional AWG optical wavelength demultiplexer.

10   Fig. 4B is a graph depicting a fundamental (local mode) field of a taper waveguide and a focal field formed on an image plane in the AWG optical wavelength demultiplexer of the present invention.   Referring to Fig. 4B, it can be found that an interference pattern having the a

15   profile similar to that of the local mode of the output waveguide is formed on the image plane in accordance with the AWG optical wavelength demultiplexer of the present invention.   In an AWG optical wavelength demultiplexer of the present invention, the input terminal of the output

20   waveguide coupled to the second slab waveguide has a taper structure in order to obtain a flat spectral response.   In Figs. 4A and 4B, the abscissa axis is indicative of the position of an image formed on the image plane.   The image formed on the image plane is an

25   image of light outputted from the second slab waveguide.

The taper waveguide is a multi-mode waveguide having a plurality of waveguide modes.   Since the waveguide mode width of the output waveguide is sufficiently large in

30   accordance with the present invention, it is possible to minimize the mode difference between the interference

pattern at the focal plane and the fundamental mode of the taper waveguide.

Fig. 5 is a graph depicting an overlap integration between the interference pattern formed on the image plane and each of the modes of the output waveguide in the AWG optical wavelength demultiplexer. In the case of Fig. 5, the interference pattern formed on the image plane is coupled to five modes, namely, the fundamental mode and first- to fourth- order modes, at the output waveguide. The abscissa axis is indicative of a normalized wavelength.

For a multi-mode coupling, an adiabatic taper waveguide structure is applied to the input terminal of the output waveguide, that is, the image plane, in accordance with the present invention. By virtue of such an adiabatic taper waveguide structure, the higher-order components of optical signals except for the fundamental mode component are cut off or radiated while passing through the taper waveguide. As a result, a final frequency response having a centrally-dipped profile is obtained. Such a centrally-dipped profile results from cut-off of coupled power of even modes at the centre wavelength of each channel. This centrally-dipped profile serves to increase the flatness of the spectral response.

In order to evaluate the AWG optical wavelength demultiplexer configured to obtain a flat spectral response while minimizing insertion loss in accordance with the present invention, a 16-channel AWG optical

wavelength demultiplexer having a wavelength band of 1.5 μm was designed. This AWG optical wavelength demultiplexer also used channel waveguides having a width of 6.5 μm and a refractive index difference of 0.75%

5   between core and cladding layers. The AWG optical wavelength demultiplexer also used a taper waveguide having a width W (Fig. 3) of 25.3 μm and a length L (Fig. 3) of 4800 μm at its output waveguide portion. In order to calculate the spectral response characteristics of the

10   AWG optical wavelength demultiplexer, a two-dimensional beam propagation method was used.

Fig. 6 is a graph depicting spectral response characteristics calculated for the above AWG optical

15   wavelength demultiplexer configured in accordance with the present invention. As shown in Fig. 6, the AWG optical wavelength demultiplexer of the present invention exhibited an insertion loss of 1.16 dB and a 3 dB passband width of 72.3 GHz. Although not taking into

20   consideration the loss resulting from coupling to the final optical fibre and loss resulting from curved waveguides, the AWG optical wavelength demultiplexer of the present invention exhibited a considerable improvement in insertion loss, as compared to the

25   conventional methods.

It is unnecessary to limit the size of the taper waveguides to a particular size as mentioned above. In accordance with the present invention, it is possible to

30   implement a variety of AWG optical wavelength demultiplexers using a variety of taper waveguides having

different sizes, respectively.

While the present invention has been described in detail with reference to certain specific embodiments, these are mere exemplary applications. Thus, it is to be clearly understood that many variations can be made by one skilled in the art within the scope and spirit of the present invention.

As is apparent from the above description, the present invention provides an AWG optical wavelength demultiplexer using taper waveguides arranged between the second slab waveguides thereof and the output waveguides thereof, thereby being capable of achieving a reduction in loss. The taper waveguides of the present invention can be applied to existing optical devices without any problem in regard to fabrication processes.

CLAIMS:

1. An optical wavelength demultiplexer, comprising:

   first means, for power-dividing the input optical signals coupled from one or more input optical waveguides;

   second means, comprising a number of waveguides, each adapted to receive a respective power-divided optical signal, and for introducing a constant phase difference between the power-divided optical signals in neighbouring waveguides;

   third means, for recombining and wavelength-dividing the optical signals output from the second means, and supplying the resultant optical signals to one or more respective output waveguides; and

   taper waveguides interposed between the third means and the output waveguides and adapted to obtain a flattened spectral response.

2. An optical wavelength demultiplexer according to claim 1 wherein the first means comprises a first slab waveguide.

3. An optical wavelength demultiplexer according to any preceding claim wherein the second means comprises an arrayed waveguide grating.

4. An optical wavelength demultiplexer according to any preceding claim wherein the third means comprises a second slab waveguide.

5.   An optical wavelength demultiplexer according to any preceding claim wherein the taper waveguide is further adapted to minimise an insertion loss.

6.   An optical wavelength demultiplexer in accordance with any preceding claim, wherein the taper waveguides are linear taper waveguides.

7.   An optical wavelength demultiplexer in accordance with any preceding claim, wherein the taper waveguides have an adiabatic structure, and are adapted to reduce a power exchange among waveguide modes during passage of optical signals therethrough.

8.   An optical wavelength demultiplexer in accordance with any preceding claim, wherein the taper waveguides have a multi-mode structure at the output terminal of the third means.

9.   The optical wavelength demultiplexer in accordance with any preceding claim, wherein the taper waveguides have the same size as the size of the output waveguides at an output terminal thereof, thereby to facilitate the coupling of the output waveguides so as to guide the optical signals into the output waveguides.

10. An optical wavelength demultiplexer substantially as described and/or as illustrated in Figs. 1-4A, 5 or 6 of the accompanying drawings.